

## **Fitting Models of the Population Consequences of Acoustic Disturbance to Data from Marine Mammal Populations**

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### **LONG-TERM GOALS**

To build an ecological modeling framework that facilitates understanding of the at-sea condition and health of various species of marine mammals. We will use the results from these models to explore and quantify the impact of different types of disturbance (both environmental and anthropogenic) on these species. Modeling will be within a Bayesian framework, which will allow us to fully account for the uncertainty in the data, the biological processes, and in model output.

### **OBJECTIVES**

Our scientific objectives are to build a statistical framework for understanding the at-sea health of (initially) three species of marine mammals: southern and northern elephant seals, and northern right whales.

For elephant seals our goal is to build a hierarchical Bayesian model that provides daily estimates of lipid status, as lipid status of the mother is directly linked to pup survival (McMahon et al. 2000). This model will use the drift dive behavior of elephant seals (Crocker et al. 1997) as the link to the underlying true, yet immeasurable, lipid state.

For right whales, our scientific objective is to build a model that provides spatially and temporally explicit estimates of individual health, movement, and survival. The model builds upon some of the ideas from the elephant seal project, but as the photo-identification of individual right whales is the core of the data, the model also includes many ideas concerning mark/recapture from (Clark et al. 2005).

### **APPROACH**

Jim Clark heads the PCAD work at Duke University with the assistance of one Postdoctoral researcher, Rob Schick. For the last fiscal year, work has focused on a) finishing the elephant seal analysis and

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submitting the manuscript for publication, and b) further refinement, development, and fitting of the right whale model to data.

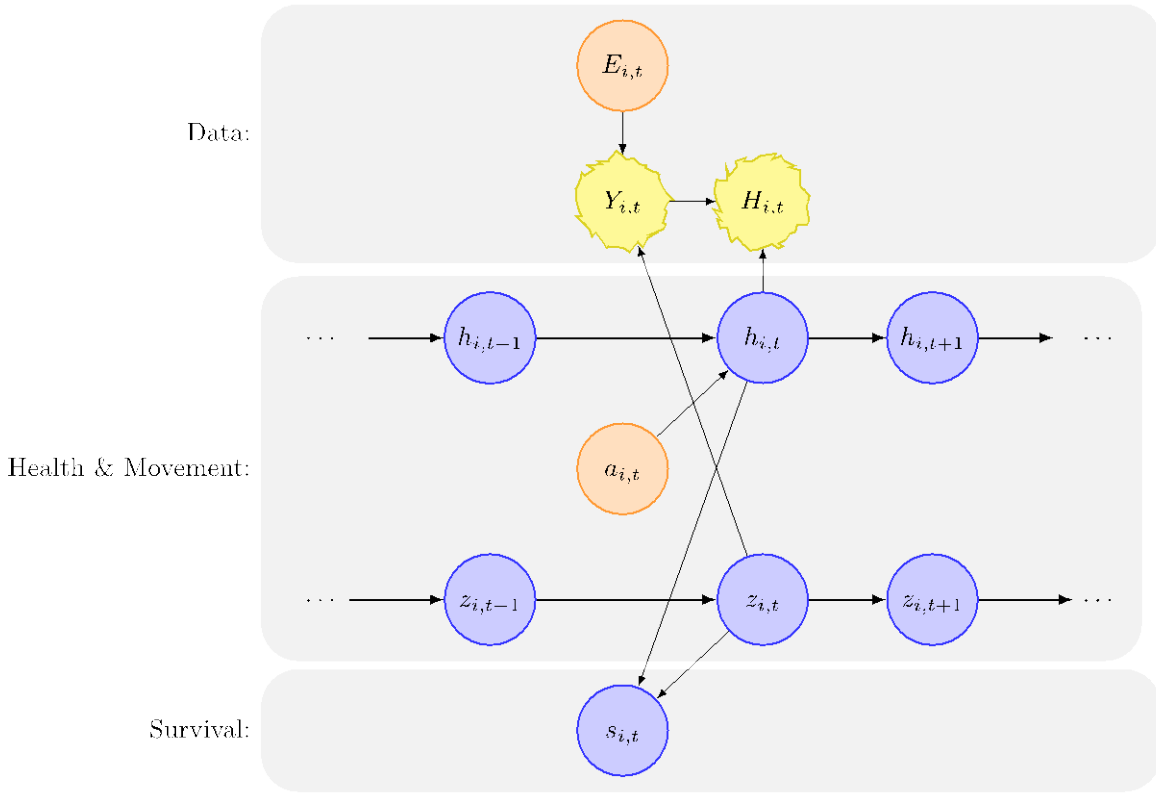
For right whales, much of our work has been on model development, and following discussions with New England Aquarium (NEAq) researchers, model refinement. After repeated attempts at model fitting that proved less than fully successful, Clark rewrote the Gibbs sampler for the main state-space component of the model. This has resulted in significantly better convergence in the model fitting, and has given us a working model framework.

Schick traveled to NEAq for a week in early May to work with NEAq researchers, including Scott Kraus, Roz Rolland, Amy Knowlton, Philip Hamilton, and Heather Pettis. The goal of this week was to discuss the modeling framework, get feedback from NEAq researchers, and begin the process of model refinement.

## **WORK COMPLETED**

Our manuscript on lipid gain/loss in elephant seals was rejected by *Ecology* in December of 2011. The primary critique was that we promised to show a full PCAD application from disturbance to population consequence, but in fact only covered a component of the transfer functions. During the early months of 2012, we rewrote the manuscript with a revised focus on the role of body condition in foraging ecology. This revision was submitted to *Journal of Animal Ecology* for publication. The manuscript was rejected in late June 2012, with the two primary criticisms being that a) the observation model we used does not sufficiently capture all the factors that contribute to drift rate, and b) our scientific hypotheses were insufficiently focused. We are currently in the process of revising this manuscript.

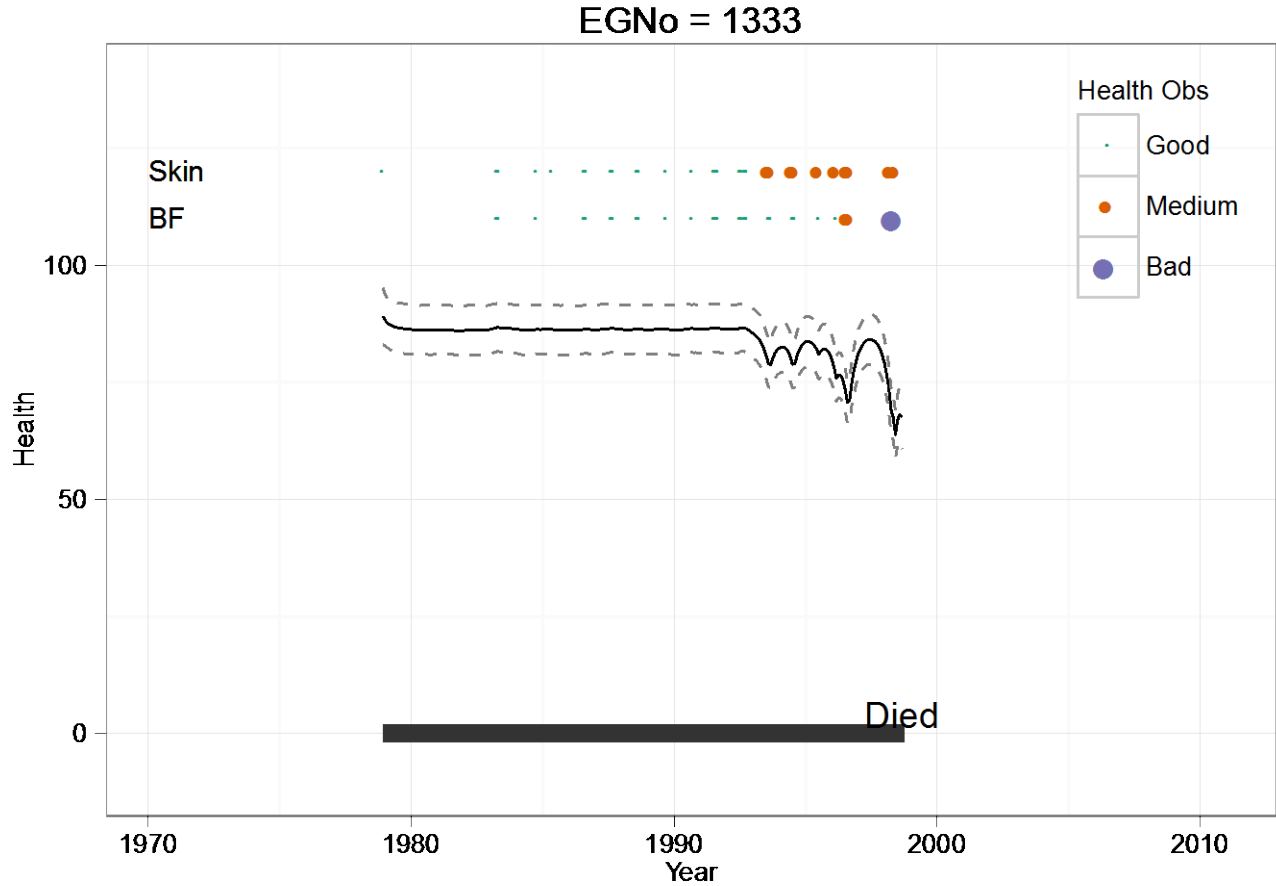
The state-space model we have developed to estimate health in right whales is comprised of an observation model, and two process models – one to estimate how health changes over time, and one to estimate how movement changes over time. In turn estimates of both health and location contribute to an estimate of survival for individual animals (Figure 1). While the time series of individual observations can be quite lengthy, within the state-space framework, the problem can be factored into lower dimensions such that a state at any given time  $t$  is conditionally dependent on the states immediately prior and following  $t$  (Clark and Bjørnstad 2004, Clark et al. 2005, Clark 2007). For our model, this means the posterior distribution for health,  $h$ , of individual  $i$  at time  $t$  is conditionally dependent on  $h_{i,t-1}$ , and  $h_{i,t+1}$ .



**Figure 1. Graphical model depicting the dependency structure in the right whale model. In the observation, or data model, we have survey effort  $E$ , sightings  $Y$ , and health observations  $H$ . In the center panel we have processes for true latent health and true movement. Currently age  $a$ , and health  $h$  at  $t-1$  contribute to health at  $t$ .**

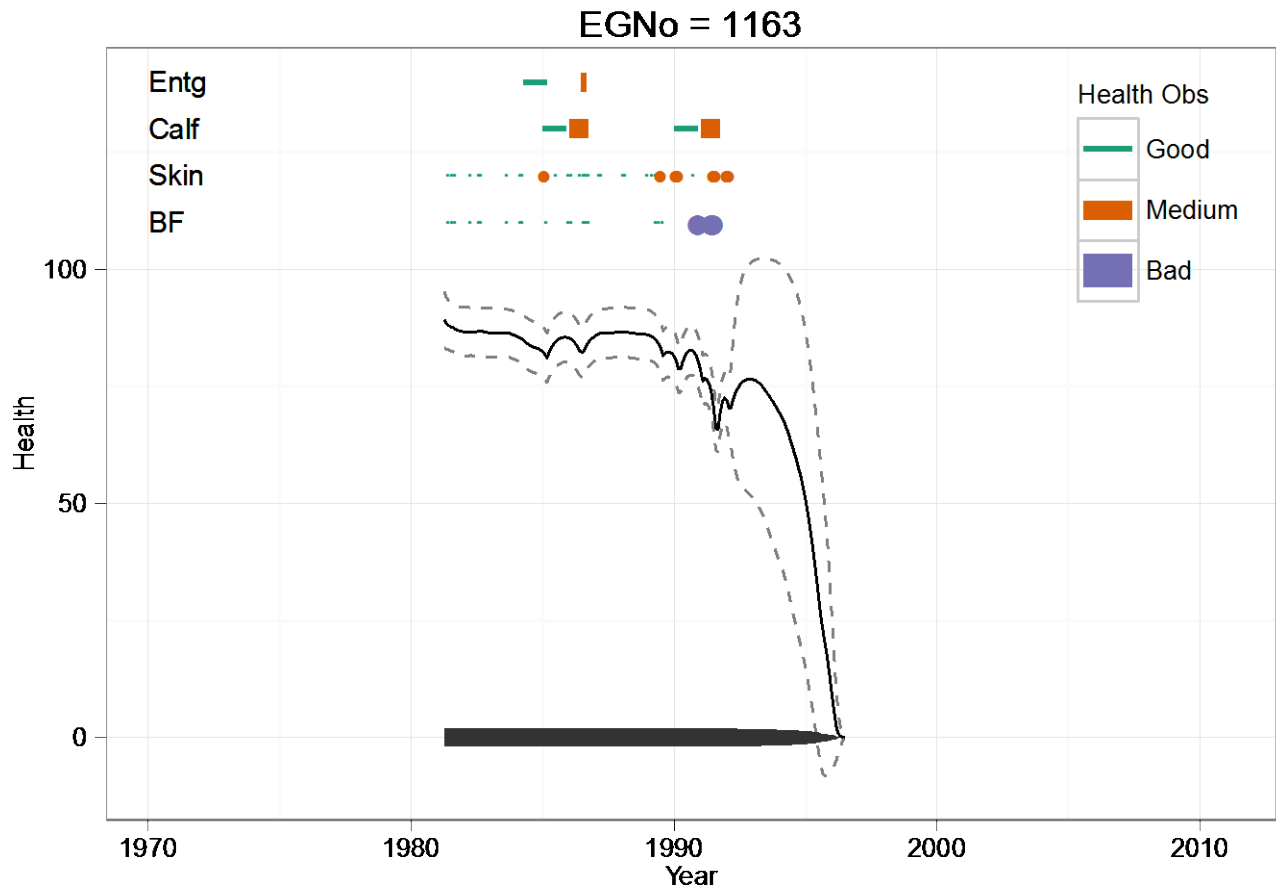
Much of our work early this year involved rewriting the R code for the Gibbs sampler to put these components together in a more coherent framework. Following this effort, we have achieved much better model convergence. The R code is somewhat slow, owing to two loops over time – one for updating the states, and one for updating health. A run of the Gibbs sampler of 10,000 steps takes about 24 hours to complete. The model has not reached convergence after so few iterations; many more iterations are needed. We are exploring ways to speed up the code by writing the two main functions in a low-level language like C.

Using the model, we have produced estimates of health for individual right whales over the temporal extent of their sighting history. For the first time we have a coherent view, with uncertainty, of how the health of individuals varies over time and space (Figure 2).



**Figure 2. Health estimates for right whale # EGN0 1333, with uncertainty, represented as solid and dashed black lines, respectively. Data observations are shown above the black lines for body fat, and for skin condition. Observations where the animal is in poorer condition are shown with orange and blue dots of increasing size. Survival probability is shown by the grey rectangle at the bottom. This animal was observed dead.**

Since we know the sighting history of each animal, and the fate of many animals, it is edifying to see how the health trajectories differ for animals in different health categories. For example, NEAq researchers know that animals coded as ‘very thin’ either are known to have died, or have never been seen again (Pettis et al. 2004). Using this information, we can visualize the health trajectories for these animals and see their downward progression in health. Some animals are known dead (Figure 2), while others are presumed dead, i.e. their death is unobserved and have not been seen since the health coding of ‘very thin’ (Figure 3). For these latter animals their health decays to 0 over time, but with much greater uncertainty (Figure 3).



**Figure 3 Health estimates for right whale #EGNo 1163, with uncertainty, represented as solid and dashed black lines, respectively. Data observations are shown above the black lines for body fat, skin condition, gestational status, and entanglement. Observations where the animal is in poorer condition are shown with orange and blue dots of increasing size. Survival probability is shown by the grey rectangle at the bottom. This animal is presumed dead.**

While much of the model development has taken place at Duke, Schick has been in regular phone and email contact with NEAq researchers. In addition, Schick made two trips to NEAq to discuss modelling progress and particulars of right whale biology. (The second of these trips was supported by ONR Award N000141210389 to Scott Kraus.) These meetings have produced several critical refinements to the model, including: 1) informed priors on movement; 2) imputation of death times for individuals; 3) how different discrete photographic observations contribute to health; and 4) how best to include entanglement status and severity in the model.

Schick has participated in three PCAD meetings: 1) the one day policy workshop in October, 2011 in DC; 2) the full PCAD working meeting following this workshop; and 3) the one day meeting prior to the ONR review in April, 2012.

Schick presented the right whale research at the Annual Meeting of the Right Whale Consortium in November, 2011 in New Bedford, MA. Prior to the RWC meeting, Schick spent the day at NEAq reviewing modeling progress, and results to date. Schick presented the right whale research on behalf of Clark at the ONR Program Review in April 2012.

Schick also traveled to Santa Cruz, CA in January, 2012 to meet with Dan Costa, Lisa Schwarz, Sam Simmons and Clive McMahon, to discuss the best ways to revise the elephant seal manuscript.

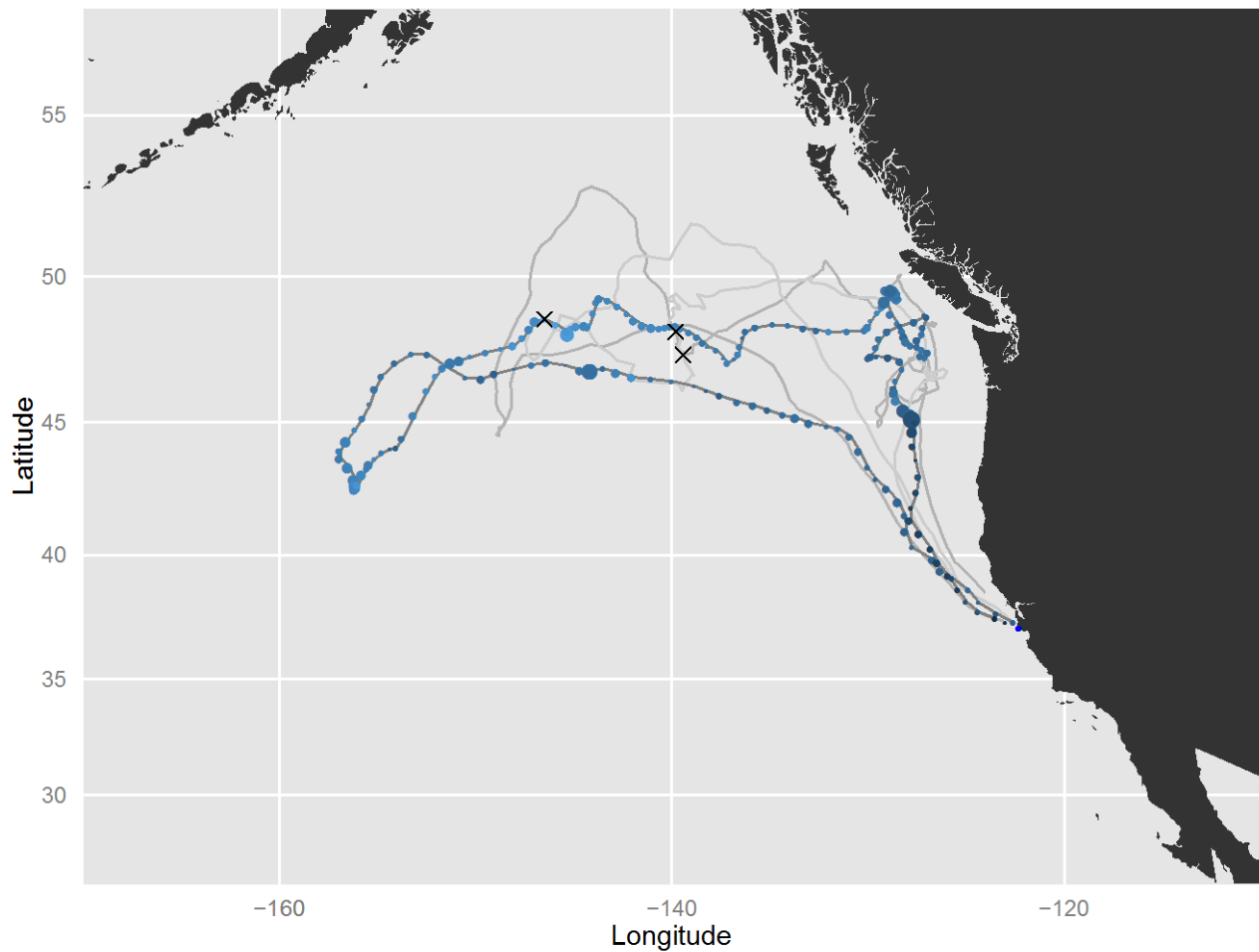
In late June, 2012, Schick moved from Duke University to the University of St. Andrews. The remaining months in FY 2012 from this Award were transferred from Duke to St. Andrews (Award N000141210286).

## **RESULTS**

We have built, and successfully fit to data, two models that provide estimates of condition in two different species of marine mammals. In the first application, we have estimated at-sea lipid content in two species of elephant seals. In the second application, we have estimated at-sea health status of individual North Atlantic right whales. In both cases, these estimates of a hidden process (lipid status and condition/health), have provided a synthetic understanding of how animals fare over broad spatial and temporal scales. With elephant seals, the understanding has focused on aspects of foraging ecology, while in right whales we have quantified more precisely how the health of individuals and of the population change over time. This understanding in right whales can lead to specific management interventions.

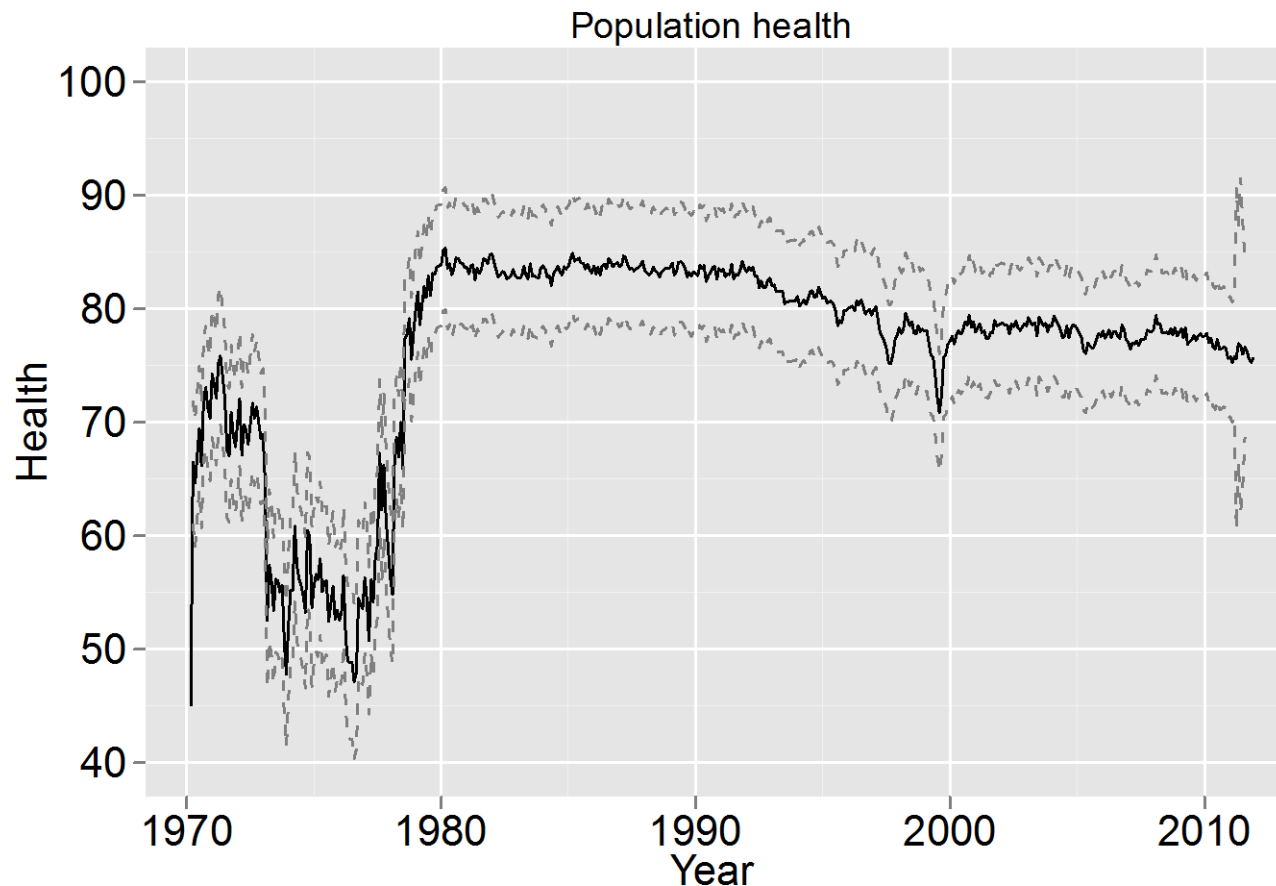
In our analysis of elephant seal data, new findings this year have centered on two results: 1) the effect of short-term behavioral states on lipid gain in Northern elephant seals; and 2) the effect of past foraging history on current lipid gain. First, we fit model formulations that included short term behavioral state (Jonsen et al. 2005) as a covariate in the lipid gain process. In southern elephant seals, the results were insignificant, i.e. short-term behavioral state had no impact (positive or negative) on lipid gain. In contrast, the effect was strongly positive in northern elephant seals, i.e. animals in a putative ‘foraging’ state put on lipids at a higher rate. This is a significant result as it shows how putative foraging states derived from mechanistic movement features can be linked to foraging success and physiological change.

Second, for a small subset of the tagged elephant seals, we were able to explore lipid gain patterns in repeated years. Most animals had a relatively fixed foraging strategy from year to year, however one female elephant seal varied her foraging strategy or location over time (Figure 4). This animal was a young adult when she was first tagged, and the results shown here (Figure 4) indicate that past foraging success is indicative of future foraging behavior. Specifically, positive lipid gain in the coastal portion of her first track appears to influence future foraging patterns. In the first tagging year the seal explored pelagic areas, before returning closer to a coastal foraging location. As she approached this coastal region at approximately 100 days at sea, she put on a significant amount of lipids (Figure 4). In subsequent years she forgoes the far west, or pelagic, foraging areas, and instead forages in the Northeast Pacific (Figure 4). This is significant, because past success should influence future patterns, even if the productivity in future foraging areas is not predictable (Bradshaw et al. 2004). While Bradshaw et al. (2004) used records of sea temperature variability to predict future foraging strategy, we have shown how positive physiological change in one year influences future behavior in subsequent years.



**Figure 4.** Map depicting the three post-moult foraging trips in one northern elephant seal (O401) across three years (2004, 2005, and 2006). Map is colored by lipid gain/loss for 2004 with lighter blue values corresponding to higher lipid gain. The tracks in 2005 and 2006 are depicted in grey lines. Size of the circles in 2004 corresponds to the number of drift dives recorded. The ‘x’ denotes the 90<sup>th</sup> day of the track for each of the three years. Note that after about 90 days out O401 starts to gain lipids rapidly. This period in the track in 2004 corresponds to a shift in strategy away from a transition zone strategy towards a NE Pacific strategy. As compared to 2004, at day 90 in each of the subsequent years the seal is located much farther to the east.

In our analysis of the right whale data, the main results have been the individual and population level assessments of health.



***Figure 5. One estimate of the mean population health over the period of analysis. Results show stable health through much of the 1980's, declining health in the 1990's, and stable, but lower, health in the 2000's. The health estimates dip noticeably in the late 1990's – a known period of low vital rates.***

While the individual results have provided additional information about how health changes over time (Figure 2 and 3), the aggregate population level information is the most compelling result (Figure 5). Specifically, we have documented stable health of the population in the 1980's, decline in the 1990's, to a stable, but lower, health in the 2000's (Figure 5). This result shows that not only are we able to capture the major periods of population-wide poor health, i.e. the early and late 1990's (Caswell et al. 1999, Fujiwara and Caswell 2001, Kraus et al. 2005), but we have shown that population health has declined over the period of the analysis and observation.

## **IMPACT/APPLICATIONS**

In the field of Biologging, there are increasing attempts to both measure and analyze physiological data from at-sea individuals. Accordingly, the modeling efforts here should have broad relevance in animal ecology. The elephant seal analysis provides insight into the specifics of physiological status of animals at fine spatial and temporal scale. Though the analysis takes advantage of a behavior that is

unique to elephant seals, the ability to estimate condition from a buoyancy proxy is possible for a large variety of marine mammal species (Miller et al. 2004). Because we are able to link in situ measurements with biology and remotely sensed data, our approach should provide a useful scientific framework on which to build.

In addition to having relevance for other cetaceans (e.g. gray whales – (Bradford et al. 2012)), the right whale analysis provides a framework for analyzing many different mammalian species – including humans. By using sporadic observations together with an underlying process model, we can infer how individuals are interacting with their environment, and how their health and condition is changing as a result.

## **RELATED PROJECTS**

This project is closely related to two other ONR awards: N000141210389 to Scott Kraus (New England Aquarium), and N000141210286 to Len Thomas (University of St. Andrews).

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